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A Multiwavelength Study of Stephan's Quintet

Jack W. Sulentic

Physics & Astronomy, University of Alabama, USA

Margarita Rosado & Deborah Dultzin-Hacyan

Instituto de Astronomia, UNAM, Mexico

Lourdes Verdes-Montenegro

IAA, Granada, Spain

Ginevra Trinchieri

OAB, Milan, Italy

Cong Xu

IPAC, Caltech, USA

Wolfgang Pietsch

MPE, Garching, Germany

ABSTRACT

Stephan's Quintet (SQ) is a compact group that we find in an atypical moment when a high velocity intruder is passing through it. The intrusion is particularly interesting because a previous intruder had stripped most of the gas from the group members. This debris field was shocked in the ongoing collision with the new intruder. This evolutionary history agrees well with observations and explains how a strongly interacting system can show low levels of star formation. We present new multiwavelength data including previously unpublished ROSAT X-ray, Hα interference filter/Fabry-Perot, ISO MIR/FIR and radio line and continuum images. These observations and previously published data provide new insights as well as support for some previous hypotheses. 1) Fabry-Perot and HI velocities allow us to unambiguously distinguish between gas associated with SQ and the new intruder. 2) Most detected emission regions are found in the remnant ISM of the NI which allows us to infer its size and present physical state. 3) The few emission regions associated with the stripped ISM of SQ include the best candidate tidal dwarf galaxy. 4) Multiwavelength data suggest that strong MIR/FIR emission from the Seyfert 2 nucleus of NGC7319 comes from dust heated directly by a power-law continuum rather than a starburst. 5) The correspondance between extended X-ray/radio continuum/forbidden optical emission confirms the existence of a

large scale shock in SQ. 6) We confirm the presence of two stripped spiral members in the process of transformation into E/S0 morphology. Finally, 7) Observations are consistent with the idea that the collision in SQ is ongoing with possible detection of HII region ablation and Rayleigh-Taylor instabilities.

Subject headings: galaxies: interactions — galaxies: kinematics and dynamics — galaxies: structure — galaxies: Seyfert — intergalactic medium

1. Introduction

Compact groups are aggregates of four or more galaxies showing projected separations on the order of ∼30-40 kpc (assuming H_o=75 km s^{-1} Mpc^{-1}) which imply space densities similar to the cores of rich clusters. Compact groups are high density fluctuations usually located in non-cluster environments (Sulentic 1987; Rood & Williams 1989). Their importance is twofold: 1) they are ideal laboratories for studying the effects of extreme galaxy interactions and 2) they are low redshift analogs of processes believed to be very important at high redshift. One can study the groups either statistically or individually. The former approach still suffers from effects of sample selection bias and incompleteness. For example, only 60 of the 100 groups cataloged by Hickson (1982) actually satisfy the initial selection criteria (Sulentic 1997). The remaining objects either violate the selection criteria, extend them beyond the originally stated limits or involve triplets (with a fourth discordant redshift galaxy projected). Since it is unclear whether triplets share the same properties as N>3 accordant redshift systems (Sulentic 2000), it appears safer at present to treat them separately. In any case, if they represent groups in the process of formation by sequential acquisition of neighbors, they will not show the same level of interaction induced phenomena as richer systems. We note that 16 triplets included in the compact group sample studied by Verdes-Montenegro et al. (2001) did not show the significant hydrogen deficiency found for systems with four or more members. They also show larger velocity dispersions than n≥4 systems (Sulentic 2000) suggesting that they are unbound systems. A new southern hemisphere sample of compact groups (Prandoni et al. 1994; Iovino 2000), selected with automated techniques, promises to minimize and quantify effect of bias, when a suitable multiwavelength database better defines its properties.

Stephan's Quintet (SQ) is the ideal candidate for detailed study because it is bright and because it is in a rare but important stage of dynamical evolution. Inferring group properties from SQ is not unreasonable because it is typical of the compact group phenomenon as defined in the Hickson (1982) catalog (see also Prandoni et al. 1994) only showing more spectacular properties because of an ongoing collision. The best example of an "active" compact group in the southern hemisphere may involve the Cartwheel galaxy (Wolter et al. The crossing time for such collisions is so short (few × 10^7 years) that more than one "SQ" is unlikely to be found in a sample of one hundred compact groups. The frequency of such collisions is a direct function of local galaxy density and SQ is not in an unusually dense environment (Sulentic 1987). 1999) where the most recent collision

occurred a few $\times 10^8$ years ago. The distribution of component velocities relative to the first ranked member in Hickson groups (Sulentic 2000) suggests that SQ is not the only group with a possible high velocity intruder nearby.

A "two intruder" (old intruder=NGC7320c=OI; new intruder=NGC7318b=NI) evolutionary model has been proposed for SQ (Moles et al.1997) that may be relevant to most compact groups and that may have relevance for our understanding of interactions at high redshift. This model forms the basis for our interpretations of the multiwavelength data. In section 2 we discuss the new observations and their reductions as well as data harvested from archival sources. In section 3 we discuss past work on SQ and compact groups in general. We combine new and old observations in Section 4 to show how they are consistent with the two intruder scenario. Section 5 summarizes important results and their implications.

2. New and Harvested Multiwavelength Observations

We present new observations at X-ray, optical, infrared and radio wavelengths as well as optical archival data that include the highest resolution (HST) and highest sensitivity (CFHT) optical images.

2.1. ROSAT X-ray

We obtained new ROSAT HRI (Trümper 1983, Pfeffermann et al. 1987) data in Dec 1996-Jan 1997 with a total observing time of 65 ksec split into 35 intervals (OBIs). These observations followed a shorter one ($\sim$ 23 ksec), already discussed (Pietsch et al. 1997), which we also include in the present analysis. We excised time patches of data shorter than 40 sec. (caused by high background rejection in the standard analysis and/or high voltage excursions, for a total of 600 sec.) and lowered the tolerance to low count rates, that excludes a higher percentage of high particle background data, mostly in proximity to radiation belts. This screening resulted in a loss of 6.4 ksec of data, but should ensure a very clean dataset. The same cleaning was applied to the old dataset, so the total observing time on SQ is $\sim$77.5k sec.

Due to the lack of strong point sources in the HRI field of view, we could not improve on the short term aspect solution used by the Standard Analysis Software System (SASS, Voges et al. 1992). We however verified that no major time-dependent effects are present in the data by accumulating and comparing images in three $\sim$ 20 ksec intervals. We found that: a) the positions of the few field sources were the same and b) a possible residual systematic effect of improper de-wobbling might still be present. Further checks confirmed a residual wobbling-related effect, so that no structure on scales of $7'' - 10''$ could be trusted. We also evaluated the absolute pointing of the observations by searching for optical counterparts to all of the X-ray detections in the field of SQ. None of the sources outside of SQ coincide with known objects (*e.g.* from SIMBAD or

NED) but faint counterparts are visible on the DSS2 for three sources. We re-aligned the absolute coordinates of the X-ray map on these sources, using in addition the radio position of the Seyfert nucleus (van der Hulst & Rots 1981). This produced a 0.4^s shift to the E. Our final positions should be accurate to $2'' - 3''$.

We considered merging both HRI datasets in order to improve the statistical significance of our results. However, since the source is not at the same detector position in both pointings (it was $\sim 4'$ off-axis in the first observation), and in light of known spatial inhomogeneities in detector gain, which also changes with time[1], we decided against it, and we use the datasets independently. Most of the following discussion is based on the second and longer observation with the shorter one used for consistency checks. To limit the changes due to gain effects, while improving on the signal-to-noise ratio, we have selected data in PHA channels 1 to 10 for both observations, which considerably reduces the background contribution (see also the on-line documentation; note that this is a larger range than used in Pietsch et al. 1997, where only PHA channels 4-8 were included). The background was obtained from a $4' - 6'$ annulus around the field center in both datasets. In the first observation, since the source itself is at $\sim 4'$ off-axis and is therefore included in this annulus, a circle of $3'$ radius centered on SQ is masked out from the background region.

Figure 2 (left panels) shows two X-ray images of SQ involving: a) adaptively smoothed (upper) and c) gaussian filtered (lower) data. The adaptive smoothing algorithm provided with the CIAO software was used (see `http://asc.harvard.edu/` for further details). We have used the FFT method with 2σ minimum significance. Table 1 summarizes the contribution of each feature, to the old and the new observations. The flux is obtained from the total count rate, converted assuming a *raymond* spectrum with kT=1 keV and the line-of-sight galactic absorption $N_H = 7 \times 10^{20}$ cm^{-2}. The flux determination is almost independent of the choice of a spectral model, given the relatively narrow energy range of ROSAT, for reasonable values of the absorbing column density (see Pietsch et al. 1998). This assumption will not be correct if significant absorption is present, e.g. in the Seyfert 2 nucleus. We have defined 4 regions: 1) a circle at the position of the Seyfert galaxy NGC7319, with r = $18''$; 2) a circle at the position of NGC 7318a (r=$15''$); 3) a rectangle of $0.9' \times 1.6'$, centered on the elongated NS feature; and 4) a smaller rectangle ($0.4' \times \sim 0.8'$) that includes only the higher surface brightness part of this feature.

Figure 2 (right panels) show: 2b) 21cm radio continuum (upper) and 2d) forbidden [NII]λ6583 (lower) images. The radio image (see Section 2.5) shows the same structure as the X-ray in: a) the elongated feature (interpreted as a collisional shock), b) the extension of this feature to the extreme NW of SQ and c) the detection of the elliptical galaxy member NGC7318a. The radio continuum image of the extended (nonthermal shock) feature is relatively stronger and broader on the south edge which may reflect attenuation of the X-ray emission due to the larger hydrogen column of foreground NGC7320 which extends over this region. The peak HI column in NGC7320

[1] see the discussion in the The ROSAT HRI Calibration Report and Users' Handbook, available on-line at `http://hea-www.harvard.edu/rosat/`

$N_H = 1.6\times10^{21}$ cm^{-2} is slightly more than twice galactic and the distribution of HI is flat so that there is more than double galactic column (9.0×10^{20} cm^{-2} from NGC7320 and 7.0×10^{20} cm^{-2} from the Milky Way) in the region where the X-ray emission from the shock is weakest relative to radio continuum.

We attempted to quantify the significance of any low surface brightness component that might be present in SQ by measuring emission in several features visible on the X-ray maps. Figure 3 shows the azimuthally averaged profile of the total emission as well as the emission averaged in two opposite quadrants along the NS and EW directions. We derived the profiles in concentric annuli of increasing size, centered on the peak of the emission in the extended feature as seen in the adaptively smoothed map (Figure 2a). The azimuthally averaged profile shows a clear excess over the background out to r$\sim 1.5'$. The emission appears to be extended roughly equally in the NS and in the EW directions. Some very low surface brightness emission could extend to r$\sim 3'$, mostly in the EW direction (right panel in Figure 3). Recently obtained CHANDRA data confirm the existance of such emission (Trinchieri et al. in preparation).

2.2. Hα Interference Filter Imaging

Interference filter observations were obtained in August 1997 with the 2.2m telescope at Observatorio Astronomico Hispano Aleman on Calar Alto, Spain (see also Xu et al. 1999). They are not the first emission line images obtained for SQ (Arp 1973; Moles et al. 1997; Vilchez & Iglesias-Paramo 1998; Severgnini et al. 1999) but they are the most sensitive and cover the entire group and effectively separate group from NI emission. Two narrowband filters (667/7 and 674/8) centered at 6667 (FWHM=66$\AA$) and 6737$\AA$ (FWHM= 76$\AA$) allowed us to separate most of the SQ emission (6300-7000 km/s) from that of the NI (5600-6000 km/s). The Hα transmission for the 667/7 filter was 0.49 for the 5700 km/s emission and 0.04 for SQ emission while the 674/8 filter yielded a transmission of 0.49 for SQ and 0.06 for 5700 km/s emission. The region of strongest overlap involves emission from the NI at $\sim$ 6000 km/s located north of the nucleus. The continuum was subtracted from both images using an R band image. Both maps were smoothed with a 2 arcsec Gaussian beam in order to increase sensitivity to diffuse emission (Xu et al. 1999). The SQ and NI emission line images are shown in Figures 4a and 4b respectively, with Figures 5a and 5b presenting, respectively, the emission line images with contours for (VLA, §2.5) HI emission in the velocity ranges 6500-6800 and 5600-6000 km/s, respectively, superimposed. Figure 6 (bottom panel) shows the appropriate wavelength ranges where emission from Hα, [NII]λ6583$\AA$ and the [SII] doublet $\lambda\lambda$6717, 6731$\AA$ are observed. In the lower panel we also indicate the filters used with appropriate FWHM. The diagram allows one to assess the degree of overlap for all the interference filter observations described in this paper.

We also used the 2.1m telescope at Observatorio Astronómico Nacional (at San Pedro Mártir, Baja California, México) to obtain three 20 minute exposures through a narrow band filter centered at 6731$\AA$ (FWHM=10Å). The observations were made with the Fabry-Perot interferometer instru-

ment (PUMA without an etalon) in the direct imaging mode. The resultant images are sensitive only to [NII]λ6583$\AA$ (+continuum) emission in the 6740-6970 km/s velocity range (SQ ISM) and should therefore image diffuse [NII] emission associated with the shock as well as discrete emission from HII regions. The full velocity range of this emission is estimated to be 6300-7000 km/s based upon our Fabry-Perot measures. This image is shown in Figure 2d. Figure 6 indicates that we simultaneously image the [SII]λ6717Å emission in NGC7320 where several of the highest density HII regions are enhanced.

2.3. Fabry-Perot Hα Imaging

The observations were carried out during the nights of October 27, 28 and 30, 1997 and September 10, 1999 with the Fabry-Perot interferometer PUMA attached to the f/7.9 Ritchey-Chretien focus of the 2.1 m telescope at the Observatorio Astronómico Nacional. The PUMA setup is composed of a scanning Fabry-Perot (F-P) interferometer, a focal reducer with an f/3.95 camera, a filter wheel, a calibration system and a Tektronix 1K$\times$1K CCD detector (Rosado et al. 1995). The main characteristics of the instrumental setup are the following: CCD readout was binned 2$\times$2, giving a pixel size of 1.2 arcsec (equivalent to $\sim$500 pc at 90 kpc) with a 10 $\times$ 10 arcmin field of view.

The F-P interferometer has an interference order of 330 at 6563 Å and its free spectral range of 934 km/s was scanned in 48 steps with a sampling resolution of 19 km/s, yielding a data cube of 48 $\times$ 512 $\times$ 512 elements. F-P observations of SQ are complicated because of the wide range of velocities present in three overlapping ranges (see Figure 6) and because the emission is so complex and extended. The large field of view and free spectral range of PUMA were indispensable for interpreting the F-P data. We obtained data cubes in the lines of Hα in the velocity range of the NI and [NII](λ 6583 Å) in the velocity range of SQ. No filter was available for a zero order observation of Hα but it appears at second order in our velocity cubes with almost identical channel–velocity correspondance (the velocity separation of the two lines is almost identical to the free spectral range of PUMA). During our first observing run we obtained two data cubes at 6750Å, three at 6720 Å and two at 6680 Å, each one with an exposure time of 60s per channel. During the second run we obtained three data cubes at 6680 Å, each with 120 s integration time per channel. Similar quality data cubes were co-added in order to enhance the S/N ratio. We thus obtained total exposure times of 1.6, 2.4 and 1.6 hours for the observations at 6750, 6720 and 6680 Å, in the first observing run, respectively, and a total exposure time of 4.8 hours for the observations at 6680 Å in the second observing run. The $\pm$1 orders fall at the edges (half power points) of the filter ranges shown in Figure 6.

The phase calibration was made by taking data cubes of a calibration lamp before and after the SQ exposures. When the exposure times of the object data cubes were of more than two hours, we obtained an additional calibration data cube between object exposures in order to ensure that no instrument flexure had occurred. We used a neon line at 6717.04 Å for calibrating the object

cubes. Reductions were carried out using the software package CIGALE (Le Coarer et al. 1993). Our data cubes in Hα are contaminated with night sky line emission which was subtracted using an interactive routine in CIGALE. PUMA data for SQ and the NI are shown as contour maps in Figure 7ab. Velocities were obtained by PUMA for virtually all emission features seen in the Calar Alto IF images (Figure 4ab) except for velocity smeared emission in the shock. Table 2 presents the velocities (column 2) for emission regions identified by number (column 1) in Figure 7. The left listing represents Hα in the NI (Figure 7b) while the right gives values for [NII] in SQ (Figure 7a). The left listing also presents literature measures for comparison (CO and HI measures are presented in the text). Hα emission with SQ velocities in the range 6350-6414 km/s is also detected in 18, 19 and 34. Column 3 lists velocities from Plana et al. 1999 whenever one of their possible velocities fell within $\pm$100 km/s of our adopted value. Other literature values are given in Column 4 (h denotes Gallagher et al. (2001); f denotes Arp (1973); o denotes corrected value for Ohyama et al. (1998) which is contaminated by broad emission at SQ velocities; all others are from Moles et al. (1998). Data quality is indicated by *, + or - following a velocity which correspond to 1σ uncertainties of 10, 20 and 30 km/s respectively. The latter usually correspond to regions where shock velocity smearing is seen. Fewer SQ velocities were obtained because most emission in that velocity range is in/near the shock where smearing and multiple velocity overlap often make reliable measurement uncertain or impossible.

All of our derived velocities in the NI and SQ that overlap with HI emission clouds (see Figures 5ab) show very close agreement with the HI derived velocities (HI velocities and channel maps are given in Williams et al. 2001). We note that a number of our velocities are in disagreement with those adopted by Plana et al. (1999). There are two reasons for this: 1) the much smaller free spectral range of the two Fabry-Perot etalons that they employed led to three or four fold ambiguity about the correct source velocities and 2) many/most of the emission regions south of NGC7318ab have velocities outside of the range of their interference filters. Similarly the apparent disagreement between our measures of two emission regions near or in common with Ohyama et al.(1998) result from their interpreting the strongest narrow line component as Hα when it is, in fact [NII]λ6583. The situation for the SQ velocity range is much more complex. All discrete source detections appear to correspond with HII regions imaged in Figure 4a. Unlike the NI data however, the SQ velocities and distribution of emission features shows no concentration or hint of ordered motion. Emission features in the far NE have been discussed in connection with the tidal tails produced by the OI. A velocity for residual Hα (actually [NII]λ6583 was measured) emission in (or projected on) NGC7319 was also given earlier. The remaining emission more directly involved with the NI will be discussed in section 4.2.

2.4. ISO Imaging

ISOCAM observations at 11.4 and 15 μm were obtained on 1996 May 23 with the *Infrared Space Observatory.* The 15μm observations were previously published in Xu, Sulentic & Tuffs (1999)

where details of the ISOCAM data reduction procedures can be found. We briefly summarize some key parameters that differ from the $15\mu m$ observations. The $11.4\mu m$ image was obtained using the ISOCAM Long-Wavelength-Channel array (32×32 pixels) with the LW8 filter ($\lambda_0 = 11.4\mu m$, $\delta\lambda = 1.3\mu m$), which is sensitive to the unidentified broad band emission feature (UIB) at $11.3\mu m$. Raster scans were made with $PFOV = 6''$, $M = 12$ steps, $\delta M = 48''$ (in-scan) and $N = 20$ steps, $\delta N = 6''$ (cross-scan). The basic data reduction was done using the CAM Interactive Analysis (CIA) software[2]. The effective angular resolution of the image is 10 arcsec (FWHM).

ISOPHT observations at 60 μm were obtained using the C100 camera (3×3 pixels) on board ISO. The observations were carried out on May 23, 1996, using the ISOPHT oversampling mapping mode (P32) with an oversampling factor of 3. The map has 16 scan lines and 9 pointings per map line, covering about $13'$ (in scan) × $6'$ (cross scan) on the sky. The $60\mu m$ map was reduced using the newest P32 data reduction package (Tuffs et al. 2001). This software takes advantage of the high sampling rate and high redundancy of P32 maps. The effect of detector transients were carefully corrected. The angular resolution of the $60\mu m$ map is on the order of $30''$ which is $\sim 50\%$ better than the detector pixel size ($45''$). Figure 8a presents the 11.4 μm image and Figure 8b the $60\mu m$ image with 15 μm contours superimposed. The group is resolved even at $60\mu m$ where NGC7319 and 7320 are the strongest sources as with MIR wavelengths. Table 2 presents $60\mu m$ flux densities with estimated errors at least 30%. The total $60\mu m$ flux is 1.26 Jy which is considerably higher than S=0.89 Jy obtained by IRAS.

2.5. VLA HI Mapping

SQ was mapped in the velocity range 5511-6862 km/s with the VLA in the C, CS and D configurations with subsequent data reduction using AIPS. Details and complete sets of channel maps can be found in Williams et al. (2001). The integration ranges were 5575.4-5810.5, 5917.5-6088.8 and 6432.1-6776.1 km/s. The resultant synthesized beam was 23.6×17.4 arcsec with an rms noise in the maps of 0.22mJy and a 3σ HI flux limit of 0.015 Jy km s^{-1} corresponding to an HI column density of 5×10^{19} atoms/cm^2. The HI mass detection limit is $2.3\times10^7 M_\odot$/beam at the distance of SQ. HI contours for SQ (6500-7000 km/s) and the NI (5600-6000 km/s) are overlaid on the corresponding Hα interference filter images in Figures 5a and 5b, respectively.

A radio continuum image was also constructed by averaging all line-free channel maps. The effective radio continuum bandwidth was 2.05Mhz with central frequency of 1416Mhz. The rms noise was 0.10mJy per beam. The synthesized beamwidth is about three times larger that the highest resolution continuum observations (van der Hulst & Rots 1981) but has about 3× higher flux sensitivity. This map is shown in Figure 2b where comparable resolution adaptively filtered

[2]CIA is a joint development by ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matiere, C.E.A., France.

X-ray contours are superimposed.

2.6. CFHT Imaging

Broadband B and R images were harvested from the 3.6m Canada-France-Hawaii Telescope archive. The observations were obtained on 21 August 1993 with the MOS/SIS (Multi-Object Spectrograph/Subarcsecond Imaging Spectrograph) in direct imaging mode. Seeing was estimated to be 0.8 arcsec (Plana et al. 1999). This archival data was kindly provided to us in reduced form by C. Mendes de Oliveira. The data were published by Mendes de Oliveira et al. (2001) with a different emphasis. The B and R-band images represent the average of 5×900 and 6×350 second exposures, respectively. The B band image is shown in Figure 9c while a B-R color map (see also Mendes de Oliveira et al. 2001) is shown in Figure 9d. CFHT provides the deepest images of SQ.

2.7. HST WFPC Imaging

Broad-band WFPC2 B, V and I images for SQ were harvested from the Hubble Space Telescope archive and processed using the standard HST pipeline. Dithered sets of images were obtained on 30 December 1998 and 17 June 1999 with total exposure times for the B(F450W), V(F569W) and I(F814W) datasets of 6700, 3200 and 2000 sec respectively. One WFPC2 pixel equals 0.09 arcsec ($\sim$35-40 pc). The earlier pointing was centered on NGC7318ab and 7319 while the later included NGC7319 and the full extent of the younger tidal tail. Rather than show the entire field of view of the WFPC images we have inset in Figure 10 high resolution vignettes from the B-band image of the most interesting regions in SQ from this dataset. The other utility of this data involves B-V colors for various components of SQ. This data was published by Gallagher et al. (2001) with a different emphasis. WFPC2 provides the highest resolution images of SQ.

3. Previous Multiwavelength Results

3.1. Radio

3.1.1. Continuum Observations

Radio continuum observations of systems as distant as SQ should involve negligible thermal emission (e.g. foreground NGC7320 is not detected) and should therefore be effective tracers of nonthermal processes such as AGN and shocks, both of which have often been attributed to galaxy-galaxy interactions. High resolution observations (Kaftan-Kassim et al. 1975; van der Hulst & Rots 1981) resolved two continuum sources in SQ from an apparently unrelated source at the north edge of the group. SQ detections involve: 1) the nucleus of the Seyfert 2 galaxy NGC7319 and 2)

an extended source in the region between NGC 7319 and the NI. The extended source has been interpreted as: 1) the signature of an ongoing collision between NGC7318a and 7319, 2) or between NGC7318a and b, as well as, 3) a shock front involving a collision of the NI with something (Allen & Sullivan 1980; Shostak et al. 1984). In the former two scenarios the enhanced radio continuum feature would arise from a very large number of supernova remnants (Van der Hulst & Rots 1981). The point source at the north end of the extended radio feature shows no correspondance with emission at any other wavelength and is likely to be a background source.

3.1.2. Line Observations

HI measures are a sensitive diagnostic of the degree of dynamical perturbation in a galaxy or group of galaxies. High resolution HI maps of SQ (Shostak et al. 1984; Verdes-Montenegro et al. 2000) reveal that almost all of the neutral hydrogen in SQ has been stripped from the component galaxies. Molecular gas content is strongly correlated with the star formation rate in a galaxy. High resolution observations of SQ (Yun et al. 1997; Gao & Xu 2000: Smith & Struck 2001; Braine et al. 2001) indicate that CO emission is associated with: a) optically identified dust clouds (inside, or superposed on, NGC7319) and b) tidal debris produced by the intruders. While no measurable HI remains in NGC7319, 3-4$\times 10^9$ $M_\odot$ of MH_2 are found along the same line of sight.

3.2. Infrared

IR emission is a sensitive measure of star formation activity in a galaxy. This is especially true of MIR wavelengths where warm dust very close to star forming regions is measured (Dultzin-Hacyan & Masegosa 1990). MIR radiation can be enhanced near sources of thermal (e.g. star formation) or nonthermal (e.g. AGN) photons. Deconvolved IRAS (Verdes-Montenegro et al. 1998, Allam et al. 1996) and ISOCAM observations (Xu et al. 1999 and Figure 8a) reveal that the bulk of the MIR emission in SQ arises from : 1) the discordant redshift galaxy NGC7320 (an Sd dwarf), 2) the nuclear region of NGC7319 and 3) two detached and compact starbursts, one in a tidal tail, produced by the OI and the other in the debris field associated with the NI (both involve strong CO detections; Smith & Struck 2001, Braine et al. 2001).

3.3. Optical

3.3.1. Broad-Band Imaging Observations

Broad band optical observations provide a direct measure of the interaction morphology of a pair or group through detection of tidal bridges/tails and diffuse light produced by dynamical stripping processes. Deep photographic images (Arp 1973) already revealed: 1) the existence of two

parallel tidal tails and 2) an envelope of diffuse starlight. The former features extend towards the OI and provide the best evidence that it has interacted with the group. The existence of two parallel tails suggest that it has been captured by SQ unless a single passage can produce both features. Surface photometry measures suggest that both tidal tails are quite blue (Schombert et al. 1990). An R-band measure of the luminous halo (Moles et al. 1998) suggest that L_{halo}=L* implying a tidal stripping timescale of about t$\sim$ 1Gyr assuming a reasonable rate of dynamical stripping (see e.g. Rabaca 1996). Two of the three core members of SQ (NGC 7317 and 7318a) show elliptical morphology with typical B-V colors$\sim$ 1.0 while NGC7319 shows barred spiral structure but without significant evidence for an ISM (Zepf et al. 1991; Moles et al. 1998).

3.3.2. Line Imaging, Photometry and Spectroscopy

Hα measures provide another direct measure of the star formation rate. Forbidden [NII] λ6583 emission is usually included in these measures and is more sensitive to shocks and nonthermal processes. Aside from the Seyfert nucleus, the other members of SQ show little or no nuclear Hα emission ((Vilchez & Iglesias-Paramo 1998ab; Iglesias-Paramo & Vilchez 1999, 2001; Severgnini et al. 1999). The strongest Hα (and [NII]) emission feature in SQ lies between NGC7319 and the NI, apparently associated with the event that gave rise to the radio synchrotron arc.

Very few published high resolution and s/n spectroscopic observations exist for SQ. In part this is because the component galaxies lack significant emitting gas and absorption line spectra for galaxies in the range B=15-16 requires long integrations and/or large apertures. This is especially true for the OI. An HI recession velocity in RC3 for this galaxy is spurious while a single absorption line spectrum reveals V=6000$\pm$200 km/s implying a velocity difference of $\sim$600 km/s relative to SQ (see §4.1 for a new value). Most published spectra involve HII regions near the radio continuum/Halpha arc or in the NI which is the only SQ member to retain significant gas. New Palomar 5m spectroscopy (Xu et al. 2001) along the N-S Hα+[NII] feature in SQ finds most emission consistent with shock excitation.

3.4. X-ray

X-ray observations of compact groups provide another independent measure of high energy phenomena in the groups as well as information about a hot IGM component. SQ was originally thought to have a strong diffuse X-ray component (e.g. from thermally heated gas; Sulentic et al. 1996) but subsequent ROSAT HRI observations (Pietsch et al. 1997) revealed that most of the emission comes from the Seyfert nucleus and the region of the radio continuum and Hα arc. The X-ray observations support the interpretation of this feature as a shock interface between the SQ IGM and an NI infalling with a line of sight velocity v=10^3 km/s.

4. Discussion

SQ is evolving through intergroup interactions but, especially through the effects of sequential intrusions by neighbors from the associated large scale structure. The connection between ongoing and past events is very clear; the SQ ISM was produced/stripped in one or more of the past events involving an OI and part of it is now being shocked by a collision with the NI. The collision is unusual because of the large velocity difference between SQ and the NI (ΔV$\sim$$10^3$ km/s). Figures 2, 4, 5, 8-10 show the new multiwavelength data supplemented with harvested archival observations. We amplify the evolutionary scenario advanced by Moles, Sulentic & Marquez (1997) by presenting old and new multiwavelength data that are largely consistent with it.

4.1. SQ Past History: Old Intruder

Past intrusions by the OI have significantly modified SQ and created the stripped gaseous environment that gives rise to the current shock and also contributed a significant mass of stripped stars to the common halo of the group (Moles, Marquez & Sulentic 1998).

SQ shows parallel tidal tails (Arp 1973; Arp & Lorre 1976), with one arcmin N-S separation ($\sim$ 25kpc assuming a distance of 90 Mpc), extending towards the OI. The existence of two tails suggests: 1) that the OI has visited SQ at least twice and also that 2) it has been captured. The latter inference is confirmed by the low line of sight velocity difference between OI and SQ (ΔV$\sim$ 0 km/s) obtained from our F-P observations (V=6583$\pm$20 km/s, confirmed by Keel private communication) showing that past estimates (ΔV$\sim$ 600 km/s) were too high. Hence the most recent encounter was slow unless there is a very large transverse velocity component.

4.1.1. The Older Tail

We interpret the southern tidal tail as the older of the two because it is broader ($\sim$9 vs. 5.5 kpc) and also shows lower optical surface brightness (our V band estimate μ=26.0$\pm$0.5 mag. arcsec^{-2}) vs. $\sim$24.4 mag. arcsec^{-2} (Schombert et al. 1990). The older tail appears to emanate from the SE end of discordant redshift NGC7320 (its full length is $\sim$100kpc if it really extends from the SE end of NGC7320 to the OI: Arp 1973; Arp & Lorre 1976). This was one of the arguments used in the past for associating the discordant galaxy with SQ (Arp 1973). It probably passes behind NGC7320 and connects to the region of NGC7318ab unless it really is associated with NGC7320. N7318b would not yet have arrived in SQ when this tail was formed. The new HI data support this hypothesis. HI contours shown in Figure 5a indicate a gaseous counterpart to the old stellar tail that indeed passes behind NGC7320 and terminates at the N edge of NGC7320 (S edge of the shock zone). This HI tail skirts the S edge of the larger eastern HI cloud and appears to be morphologically and kinematically distinct from it with a continuous velocity gradient $\sim$ 6560-6730

km/s from east to west (S end of old stellar tail to S edge of the shock). The large eastern HI cloud shows less ordered velocities between 6540-6670 km/s (Williams et al. 2001).

The HI tail is connected, via the shock zone, with another (albeit denser and more compact) HI cloud to the north (Figure 5a) with similar velocity range (6700-6750 km/s). The connectivity in velocity is clear. The physical connectivity is also clear because the currently shocked gas was most likely HI before the arrival of the NI. We suggest that all of this material (north cloud, shock region and HI tail behind NGC7320) represents gas that was stripped in an earlier passage of the OI. The origin of this stripped gas might be ascribed to an encounter between the OI and one of the elliptical members (NGC7317 or 7318a). Certainly either of these galaxies could reasonably have been near the north end of this tidal structure $\sim$1 Gyr ago. The evidence is circumstantial: a) an old stellar/HI tidal feature that most likely originated in an interaction between the OI and one or more SQ members and b) an excess of early type galaxies in SQ which is found in a noncluster environment where $\geq$75% late-type galaxies are expected. Indeed most nearby members of the same large scale structure component to which SQ belongs are spirals (see e.g. Shostak et al. 1984). NGC7319 is the only one of the three "core" SQ members (NGC 7317, 18a and 19; with $\sigma_V \sim 0$ km/s) that can be classified as a spiral. The continuity between the northern HI cloud, the shock zone, the HI/old stellar tail behind the interloper motivates us to favor an origin for this structure in an earlier passage involving the OI. An interesting piece of evidence in favor of a two intrusion hypothesis for production of the twin tails – via interaction with the OI – involves the observation that the older tail is not continuous (see Plate 6 in Arp & Lorre 1976). The fainter tail shows a clear bifurcation or "scalloping" ($\sim$1.2 arcmin from the S end of NGC7320) just beyond the part that shows overlapping HI emission. This structure is qualitatively consistent with the hypothesis that the OI perturbed its older tail in the process of making the younger one.

One cannot rule out the possibility that the most recent passage of the OI split the HI disk of NGC7319 ejecting gas both E and W. This possibility requires exploration with models. In this view at least some of the gas involved with the current shock originated in NGC7319. We do not favor this view because it would leave the older tidal tail unexplained unless a single encounter can produce twin and parallel tails. It would also be difficult to account for the 6700 km/s HI cloud located NW of NGC7319. The continuity between this cloud, the shock zone, the HI tail behind the interloper NGC7320 and the faint optical tail motivates us to favor an origin for this structure in an earlier passage involving the OI. This interpretation points toward an even more significant role for secular evolution in compact groups.

4.1.2. The Younger Tail

The younger (narrower and higher surface brightness) tail ($\sim$40 kpc in length) is primarily a stellar feature with HI overlapping only the outermost 10-15kpc (Figure 5a). The HI does not conform to the shape of the stellar tail in the overlap region although the tail appears to curve along the inner side of the HI distribution where the HI intensity gradient is steepest. The younger tail

connects directly with NGC7319 leading us to assume that both the tail and HI cloud originated in the ISM of this galaxy and were stripped during the most recent encounter. The B-band CFHT image (Figure 9a) shows that the tail is distinct from the SW spiral arm, or broken ring, of NGC7319 and suggests that the OI passed from NW to SE, parallel to and just west of, the bar in NGC7319. Figure 9a shows at least three distinct "streams" of stars extending from NGC7319; one coming from the W arm, one from the direction of the central bar and a central one (which most likely traces the path of the OI) from the interarm region. The streams converge into a single narrow tail about 10-20 kpc SSE of NGC7319.

Star-gas decoupling in tidal tails has previously been attributed to interactions between the gaseous component and starburst winds (Heckmann et al. 1990) or with collisionally heated halo gas (Barnes & Hernquist 1996) neither of which is supported by our observations. The recent models show that such offsets arise naturally in low inclination prograde encounters (Mihos 2001; see also Hibbard et al. 2000). As observed, and expected from such models, the stellar and gaseous components are linked in the most distant parts. The decoupling sets in as material deeper in the galaxy is stripped with increasing effects of dissipation on the gaseous component (Mihos 2001). This suggests that the length of the pure stellar part of the tail should be a direct measure of the details of the encounter (relative velocity of intruder and orientation relative to the target disk). The data favor a low velocity passage by the OI and at low inclination relative to the plane of NGC7319 (see Gordon et al. 2001 for an opposite example). The data suggest that the earlier intrusion of the OI was of a different kind that did not lead to a star-gas decoupling.

While disturbed the spiral structure in NGC7319 is not shattered. This observation and the fact that the stellar streams feeding into the tail appear to pass in front of the arm, suggest that the OI made a slow passage across (and above) the disk. The HI cloud coincident with the end of the younger tail is the most massive detected in SQ (M$\approx 4.0\times10^9$M$_\odot$). It shows velocities in the range 6540-6670 km/s (see intensity contours in Figure 5a) consistent with an origin in NGC 7319. The cloud is better described as a "wall" of HI rather than a tail because it is uniformly displaced about one galaxy diameter E and S from NGC7319. It extends more than 50 kpc north from the optical tail and the minimum separation between the W edge of the cloud and the E side of NGC7319 is $\sim$30 kpc.

Little line emitting gas remains inside NGC7319 except for that associated with the AGN. Examination of Figure 4a reveal a few weak Hα emitting regions associated with the stellar tail and HI cloud: 1) two near the tip of the tail (see also Figures 10ab) and 2) a few small regions near the north end of the HI cloud (for the brightest see Figure 10c). These emission regions are located just inside the SQ facing edge of the HI cloud where the intensity gradient is steepest. One of the features in the tail (Figure 10a) was detected by ISOCAM (Xu et al. 1999 source B). It is identified as star cluster candidate 7 in Gallagher et al. (2001). Our Fabry-Perot measures yield a velocity V=6617$\pm$20 km/s for this region, consistent with the HI velocities in the area, and with an origin in NGC7319. This source shows MIR and Hα fluxes about one tenth as strong as in starburst A (Xu et al. 1999) that lies at the north edge of the shock. This implies a star formation rate of less than

0.1 $M_\odot$/year for starburst B. This emission region may be heavily obscured as it is bisected by an opaque dust lane (see Figures 4a and 10a). The associated strong dust feature no doubt accounts for the ISO detection of starburst B. The emission regions in the tail are either remnants from a past star formation event associated with the creation of the tail or new condensations. WFPC2 images show that the weaker emission region (Hα flux S_{alpha}= 0.4$\times10^{-15}$ ergs cm^2 s^{-1} or about 0.3$\times$ starburst B) near the extreme tip of the tail (Figure 10b) is involved with a bright segmented condensation of blue stars that extends for 8 arcsec=3.6 kpc along the tail. We measure B-V=0.2 (from the WFPC2 data) for this condensation. B-V colors in the paper were estimated relative to those reported for sources in Gallagher et al. (2001). Such a very blue B-V measure is found at the extreme end of the color sequence for peculiar and interacting galaxies (e.g. Larson & Tinsley 1978; Schombert et al. 1990) and is certainly consistent with the hypothesis that a very recent star formation event occurred there. Most of this star formation would have begun after the tail was formed (see age estimates below). The brighter Hα emitting region (starburst B) $\sim$15 kpc from the tip of the tail is much more gas/dust rich and is apparently in an earlier stage of starburst activity.

If these two regions are condensing in the tail then they are the best candidate for tidal dwarf formation in SQ. SQ has been frequently mentioned as a potential site for the formation of tidal dwarf galaxies (Hunsberger et al. 1996; Plana et al. 2000; Iglesias-Paramo & Vilchez 2001; Gallagher et al. 2001; Braine et al. 2001). Models have successfully produced mass concentration in excess of $10^8 M_\odot$ either inside, with subsequent ejection from interacting galaxies (Elmegreen et al. 1993) or tidally unbound debris (Gerola et al. 1983). Such a process takes time to develop (e.g. 10^8 years for significant star formation to occur; Elmegreen et al. 1993) which rules out all emission components west of the shock where all timescales are less than this value. Unfortunately the Mendez de Oliveira et al. (2001) velocity measures did not cover the regions of the tidal tails. We suggest that the local velocity gradients that they identify in or west of the shock are largely consistent with a larger scale velocity gradient (Section 4.2.2) that reflects the residual angular momentum in the NI disk. Some of the HII regions south of the NI are quite large (D$\sim$400-500pc) but, if our interpretation is correct, they are large because they are in the process of shock ablation. The best, and probably only viable candidates in SQ involve starburst B and the blue concentration located, respectively, near or at the tip of the new tidal tail. Detection of significant CO emission (Braine et al. 2001) provides further support for the candidacy of starburst B near the end of the younger tail (Figure 4a and 10a). All of the emission features on the E side of SQ fall on or near the inner side of the HI cloud where a relatively steep velocity gradient is observed (Figure 5a). The HST WFPC2 images suggest that all of the other candidate tidal dwarfs/emission regions in the tail are stars or background galaxies.

The most intriguing condensations are found near the north end of the HI cloud that lies east of NGC7319 (Fig. 5a and 10c). The two brightest objects are identified as star cluster candidates 30-31 (Gallagher et al. 2001) but their light is dominated by line emission (e.g. they are not detected in the Hα IF image tuned to the NI velocity range. They are located more than 30kpc E from that galaxy and N of the stellar tail. The very deepest photographic images (Arp 1973)

reveal small condensations of luminous debris here as well as more filamentary structure. Such features are so faint that it is tempting to associate them with galactic cirrus (e.g. Sandage 1976). This is unlikely to be the case for the emission clumps detected in Figure 5a. Our Fabry-Perot velocity measure for the brightest of these condensations (V= 6627 km/s) agrees very well with HI velocities in the same area. This emission region shows a curious double structure (Figure 10c) and is superimposed on a faint linear feature (Plate 6; Arp & Lorre 1976) that extends towards the NE. The most straightforward interpretation is that we are seeing the formation of extragalactic HII regions in the stripped ISM of NGC7319.

4.1.3. Estimating Ages for the Tails

An important chance to advance our understanding of the OI intrusions involves estimates of timescales. There are several ways to do this: 1) estimating the orbital period of the OI by using the tails as an orbital tracer, 2) estimating a diffusion timescale for the old tidal tail relative to the new one and 3) using the colors of the blue tails to infer a timescale by assuming that the tails began with a starburst event. An even more simple-minded approach involves asking how long it would take material at the edge of the disk in NGC7319 to reach the tip of the tail traveling at V$\sim$200 km/s (assumed orbital velocity when inside NGC7319) which yields t=2×10^8 years.

One can use the shape of the tails to extrapolate the projected orbit of the OI on the sky. The simplest approach for orbit estimation involves assuming an approximately circular orbit with projected diameter equal to the current distance between NGC7319 and the OI (3 arcmin$\sim$78kpc) which yields an estimated time t=2.5×10^8 years since the encounter with NGC7319 and about 7.5×10^8 years since the old tail was produced (following a possible encounter with NGC7318a). This estimate assumed ΔV= 300 km/s between the OI and SQ. The bulk of this motion is transverse since our Fabry-Perot measure (also Keel, private communication) indicate that there is no significant line of sight velocity difference. The above timescale estimate represents a reasonable lower limit. The shape of the tails, and the clear evidence for a last perigalactic passage inside the W arm of NGC7319, raise an interesting question about the baryonic center of mass in SQ. The obvious guess would be that the center of mass lies near the center of the light distribution which would place it on or near to NGC7318a and at least 20-40 kpc W of NGC7319. The tidal tails then place it at least one galaxy diameter too far to the east. This may imply a very flat mass distribution and a center of mass ill-defined or defined more by non-baryonic than visible matter.

The old tail is fainter and more diffuse with a surface brightness similar to the feature found in the Centaurus cluster (Calcaneo-Roldan et al. 2000) but the conditions in SQ mimic a cluster environment in many ways. We assume here that the old tail was as broad as the young one one orbit ago. It is difficult to find quantitative estimates for the diffusion timescales of tidal tails. Recent models suggest that tidal tails are more easily generated in shallow potentials (Dubinski et al. 1999). This is perhaps consistent with the previous discussion about the implied orbit of the OI. Surprisingly, in view of the nature of the encounters in SQ, (and compact groups in general)

close encounters are found to be more effective in generating straight tails (Dubinski et al. 1996). The models predict that most of the motion lies along the tail. The streaming seen in the young tail on CFHT and WFPC2 images certainly supports that expectation. Transverse motions in tails are generally expected to be quite small. If we assume a transverse velocity of 15 km/s, and ask how long it would take for the new tail to assume the width of the older one ($\sim$4.5 to $\sim$ 9 kpc), we obtain t= 2-5$\times 10^8$ years.

It has been demonstrated that tidal tails are usually bluer than the galaxies involved in the interactions that produced them (similar to the colors of spiral galaxy disks from which most originate: Schombert et al. 1990). The bluest tails show B-V=0.2-0.4. We adopt 0.4 as a typical value for a young tail that still shows significant star formation. This assumption is supported by the B-V=0.4 measure (Schombert et al. 1990) for the source A starburst (Xu et al. 1999) involved with the ongoing collision in SQ. The same observations report B-V=0.57 for the younger tail consistent with a B-V=0.2 change in color. Estimates for the timescale for such a B-V=0.2 change (Wallin 1990; Bruzual & Charlot 1993; Calcaneo-Roldan et al. 2000) yield t= 2-4$\times 10^8$ years. This assumes that the star formation in the tail was quenched when the tails were formed. As discussed earlier, parts of the tail are much bluer presumably due to star formation initiated well after the tail was formed. This makes the inferred color change a lower limit to the age of the tail. We note that twisting is also predicted in some of the Wallin (1990) models. The WFPC2 images show clear evidence for twisting in the younger tail with a prominent twist being visible in the region shown in vignette A of Figure 10. A population of bright (M_V= -9 to -11) star cluster candidates have been identified (on the WFPC2 images) in the tail with ages (1×10^7 to 5×10^8 years) consistent with coeval formation with the tail or in succeeding star formation activity (Gallagher et al. 2001).

All estimates are consistent with an age for the new tail between 2 and 4$\times 10^8$ years, the event that stripped the ISM of NGC 7319. If we assume that this represents half an orbital period then the old tail was produced 6-12$\times 10^8$ years ($\approx$1 Gyr) ago. SQ is particularly interesting because it contains both old and new tidal tails. This allows us to make cautious inferences about the probable evolution of a tail over a period of $\sim$1Gyr. Other tails studied so far include those with estimated ages similar to both the old (Hughes et al. 1991; Mirabel et al. 1991)and new (Mirabel et al. 1992) SQ tails. The observed difference in surface brightness between the two SQ tails suggest that $\leq$ 1 Gyr will be sufficient for the older SQ tail to diffuse beyond detectability and, presumable, contribute to the diffuse stellar halo which in SQ is estimated to have an integrated luminosity $\sim 1L_*$ (Moles et al. 1998). SQ shows similarities with other tails: 1) a dust component, 2) the site of significant star formation well after the tail was formed, and 3) blue condensations near the tip of the tail (Hughes et al. 1991; Mirabel et al. 1991, 1992). The dust feature in the SQ tail is much more well defined than the one seen in Leo triplet. WFPC2 images show it as a well defined feature similar to the lanes observed in the disks of spiral galaxies. The dust feature follows the edge of the presumably associated HI cloud and suggests that all components of the disk in NGC7319 were pulled (unravelled) into the tail but shortly inside the innermost part of the dust lane the observed HI decoupling set in. The dust lane is either involved with or partially

obscures starburst B which is a reasonably strong MIR source (Figure 8a). Perhaps the assumed older (Rots 1978) Leo triplet plume indicates that this younger dust feature will diffuse out over the next Gyr. The blue condensation at the tip of the SQ tail is the bluests of any studied in detail so far. The weakness of associated Hα emission suggests that a burst of star formation recently ended here. The WFPC2 B-band image suggests possible decoupling of this feature from the rest of the tail while the V and I band images show much more continuity.

4.1.4. NGC7319 and 7320c–Spirals in Transition

The observations point toward a significant role for secular evolution of galaxy morphology in compact groups with spiral members likely being transformed into E/S0's. There is a clear analogy with the "galaxy harassment" process in clusters (e.g. Moore et al. 1999). The analogy is, of course even more appropriate for the NI with its cluster-like velocity relative to SQ. While we cannot prove that either NGC7317 or 7318a were originally spirals, NGC 7318b and 7320c are clearly in morphological transition.

The fact that we can still classify NGC7319 as a spiral (with a broken ring structure) galaxy is further support for our inferences that: 1) it has not been involved in a direct collision and 2) it was stripped 0.2-0.6 Gyr ago. The latter inference is motivated by the fact that the spiral structure, while lacking emission regions, is still well defined indicating that the last locus of star formation is still recognizeable. The same can be said about the OI which shows residual spiral structure and is classified RSXS0 in the RC3. Radial profiles of this galaxy reveal a bright central bulge surrounded by a disk/ring component. This structure is surrounded by low surface brightness emission with residual spiral arms. Both NGC 7319 and 7320c have lost all/most of their ISM and the OI may also have lost its disk component. The HI disk of the OI is part of the old tidal feature discussed earlier. NGC7319 has lost all detectable (upper limit $\sim 10^8$ M$_\odot$) HI, the vast majority of HII regions (expected in a typical ~SBb spiral) and an uncertain fraction of stellar mass. A few CO clouds have been detected across the face of NGC7319 (Yun et al. 1997, Gao & Xu 2000; Smith & Struck 2001). They show little correspondance with the spiral arms and may simply involve debris above the plane of the disk and unrelated to the galaxy. Evidence supporting this suggestion involves the correspondance between the CO clouds and dust patches which can be seen in silhouette against the disk on deep images.

At this epoch NGC7319 is without an ISM that could sustain the star formation necessary to propagate and define a population I spiral pattern. The brightest condensation of young blue stars (B-V=0.4-0.5) are found on the NE edge of the disk: 1) just outside the largest Hα + molecular gas concentration found along the line of sight to NGC7319 and 2) on the side opposite from the inferred path of the OI. This condensation of Hα and CO emission in NGC7319 (Figure 10d) is ~8kpc NNE of the nucleus. CO and Hα observations give consistent velocities V= 6800±20 km/s, with an inferred H2 mass of 4-7$\times 10^9$ M$_\odot$ (Yun et al. 1997; Gao & Xu 2000; Smith & Struck 2001). Star cluster candidates identified in this area (Gallagher et al. 2001) show colors consistent with

ages in the range 8×10^6 to 1×10^8 years.

The (V-band) luminosity of the younger tail L_{tail}= 0.10-0.15L_{N7319} which suggests that the most recent encounter contributed approximately that fraction of the total diffuse halo mass where $L_{halo}\approx L^*\approx L_{N7319}$ (R band measure: Moles et al. 1998). The B-band fraction would be considerably higher because: 1) significant *in situ* star formation likely occurred after the tail was formed and 2) the diffuse halo is considerably redder than the tail (Schombert et al. 1990; Moles et al. 1998). The OI is undetected in all HI surveys including the sensitive observations discussed here. In addition to morphological evidence that it is/was a spiral galaxy we can add the results of recent unpublished 2D spectroscopic mapping at KPNO (Keel, private communication) that reveals weak Halpha+[NII] emission showing ordered rotation. NGC7319 and 7320c will presumably slowly transform into lenticular or elliptical (if interactions destroy the stellar disks) galaxies. This will enrich SQ with early type galaxies. Such an excess of early type E/S0 galaxies in compact groups is well established (Hickson et al. 1988) and there is little evidence that this excess might, instead, have arisen from mergers (Zepf et al. 1991). In another ∼Gyr SQ will have no spiral members unless another intruder arrives or unless NI loses a large amount of kinetic energy.

4.1.5. The Seyfert 2 Nucleus of NGC7319

The central region of NGC7319 is luminous from X-ray to radio wavelengths. Most of this luminosity is assumed due to the Type 2 AGN hosted there. A radio continuum survey of compact groups (including SQ) revealed a deficit of global radio emission from member galaxies, but an excess of compact nuclear emission in the spiral components (Menon 1995). While most of the gas will be stripped from galaxies in compact group environments, some undetermined quantity is efficiently channeled into the center giving rise to active nuclei (Coziol et al 2000). More recent high resolution and s/n observations of the Seyfert 2 nucleus in NGC7319 (Aoki et al. 1999) reveal a smallscale (∼ 5 arcsec) triple lobe radio continuum structure.

NGC7319 contributes more than half of the MIR/FIR emission observed from SQ (Figure 8ab) which raises interesting questions: 1) should this flux be added to the FIR fraction assumed due to star formation or 2) does this emission arise from dust heated more or less directly by the nonthermal source. It is clear that the emission is thermal in origin because an extrapolation of the radio nonthermal power-law would not have been detected by IRAS or ISO (see radio continuum and IR fluxes in van der Hulst & Rots 1981; Allam et al. 1996; Verdes-Montenegro et al. 1998; Aoki et al. 1999). Without a star formation contribution from the nuclear region of NGC7319, SQ shows a strong (FIR) deficit rather than an excess in contrast to the interaction induced star formation enhancement that is observed, for example, in binary galaxies (Xu & Sulentic 1991). But this is not surprising given that almost all nonstellar matter in SQ is no longer bound to individual galaxies. Conditions in the NGC 7319 ISM "debris field" north and east of the younger tail apparently do not favor condensation and star formation (at least in the first 0.4±0.2 Gyr) – except for a few isolated clouds inside and north of the younger tidal tail (section 4.1).

Many Seyfert 2 nuclei show evidence for a near nuclear star formation enhancement. In fact some may not be AGN at all (Dultzin-Hacyan & Benitez 1994). In the case of NGC 7319 there is little evidence for a nuclear starburst. HST images of the nuclear region (the central 2×2 arcsec: Malkan et al. 1998) show complex bright and dark spiral structure but no evidence for star formation condensations. Radio continuum (Aoki et al. 1999) and supporting optical slit spectroscopy (Aoki et al. 1997) show evidence of complex internal jet+ triple-lobe structure on a scale of 10 arcsec but no signature of star formation. The high surface brightness structure seen in the inner kpc by WFPC2 is no doubt the source of the line emission seen on slit spectra. But this region is dominated by forbidden emission rather than a starburst signature. We compared the stellar psf with the nuclear H$alpha$+[NII] emission in NGC7319. The psf for stars in and near NGC7319 on the average of our Calar Alto R-band continuum images (taken immediately after the emission line images) give a consistent FWHM=3.5 arcsec (the seeing was not good). The Hα+[NII] emission line psf gives a similar psf (3.5-4.0 arcsec) except for a wing extending about 10 arcsec to the SW. The wing corresponds to the mostly forbidden emission studied by Aoki et al. 1997). The seeing disk therefore matches well the field imaged by WFPC2 where no evidence for significant starburst activity was found.

There is conflicting evidence for the presence of molecular gas in the nucleus of NGC7319. Demonstration of significant molecular emission from the nucleus would support the argument that significant star formation was occuring there. Yun et al. (1999) detect a small cloud about 2kpc S of the nucleus but Xu & Gao (2000) place this source on the nucleus. We favor the former interpretation because the former (somewhat higher resolution) centering coincides with an optical dust patch seen in silhouette and the CO emitting region is clearly extended and not concentric with the nucleus. Thus it may well be a projected cloud of tidal debris rather than a concentration of molecular gas in the immediate nuclear region. In any case, the mass of molecular gas there is $\leq 2\times10^8 M_\odot$ inconsistent with the bulk of the observed MIR/FIR emission originating in a hidden nuclear burst. If one interprets the Seyfert 2 nucleus of NGC7319 as a product of the most recent encounter with the OI then: a) only a small quantity of gas escaped the stripping event, 2) this small quantity was quickly and efficiently channeled into the innermost regions, 3) it gave rise to an AGN with associated small-scale radio lobes and an optical jet structure involving shocked gas, 4) little star formation is/was involved with this process and 5) the dusty nuclear environment is likely heated more or less directly by the power-law continuum of the AGN which reenforces our inference that the FIR signature of star formation in SQ is very weak.

4.2. SQ: The Ongoing Collision

4.2.1. The SQ ISM

We assume that NI was not inside, or near, SQ when the interaction events described in the previous section transpired. Reasonable crossing times (t_c= 2–8$\times10^7$ years) for NI are 5-10× less

than the estimated time since the last encounter between SQ and OI. Any shocks generated by past intrusions would have cooled, unless they involved very low density ($n_e\sim10^{-2}$–10^{-3} cm^{-3}) gas, and most interaction-induced star formation activity would have ended. We observe an X-ray and Hα+[NII] extension (Figures 2c and 4a) from the N-S oriented shock zone towards NGC7319. Its orthogonal orientation with respect to the shock motivates us to interpret it as related to the ongoing events. The most important inputs into our inferences about ongoing events involve: 1) the configuration of the stripped ISM in SQ before the arrival of NI and 2) the trajectory and overall structure of NI. We suggest that Figure 5a provides the most reasonable estimate of the immediate pre-shock SQ ISM. This superposition of HI (contours) on Hα+[NII] emission represents all warm and cold gas (except molecular) in the SQ velocity range. [NII] emission (Figure 2d for the brightest part of the shock and Figure 4a for more extended diffuse emission) also traces the location of the hot gas. If one replaces the regions showing shocked gas with HI then one should have a reasonable idea of the pre-shock ISM.

Velocities of stars and gas associated with SQ span a range from 6400-7000 km/s (Figures 4a, 5a and 7a; Table 2). The gas surrounding NGC7318ab spans the velocity range 5400-6000 km/s (Figures 4b, 5b and 7b). Therefore NI velocities are found in, or west of, the shock while SQ velocities are found in, or east of, the shock. The only exception to this rule involves a radio, X-ray and Hα+[NII] extension (towards an emission condensation with an uncertain Fabry-Perot V$\sim$ 7000 km/s) towards the extreme NW of SQ. The SQ and NI emitting regions are reasonably well separated in the IF images shown in Figures 4ab. Some redundancy exists due to overlap in the filter responses in the velocity range 5900-6400 km/s (Figure 6). Fabry Perot velocities are given in Table 2 for all of the detected emitting regions which are numbered on the contour plots shown in Figure 7.

We find HI clouds with unambiguously SQ velocities (Figure 5a): a) north of the NI, b) south of the NI, passing behind NGC7320 and superimposed on the old optical tail, as well as c) the largest cloud located ESE of NGC7319. Clouds b) and c) appear to be structurally and kinematically distinct with b) part of an old tidal feature, perhaps involved with the stripping of NGC7318a or 7317, and c) involved with the more recently stripped ISM of NGC7319. We suggest that clouds a) and b) are linked by the shock region where we find Hα+[NII] emission (Figure 5a). Gas in the region of the shock would have been largely cold (like HI clouds a) and b)) before the arrival of the NI. This is a reasonable hypothesis because of the long estimated time since the last encounter and because of the small amount of Hα emission observed in optical and HI tidal features produced in past events (making it likely that little or no Hα in the shock region, with SQ velocities, is related to past events). One possible problem with this "linkage" involves the higher density and roughly circular shape of the northernmost HI cloud. We argue that the velocity continuity argument carries more weight. And the fact that, at least, a projected linkage is undeniable in the absence of the current shock conditions. Finally, the HI in tidal features is clumpy and the north clump would be nearest the impact point that produced this assumed tidal feature.

The high velocity passage of the NI through the stripped gas (the gas between components

a and b above) gives rise to the shock. All relevant timescales connected with this event are less than 10^8 years: a) NI crossing time, b) decay of the radio synchrotron emission ($\sim 8\times10^7$ years; Van der Hulst & Rots 1981), c) the shock cooling time, d) the age of Starburst A in SQ ISM on the north edge of the shock (1–2×10^7 years; Xu et al. 1999) and e) the ages of the bluest star cluster candidates identified in SQ (consistent wiith ages 5-7 $\times10^6$ years). Thus we assume that this is an ongoing collision. The implication of this assumption involves evidence in our data that: 1) the ISM of the NI is not yet completely stripped and 2) we are seeing NI HII regions in the process of ablation (see Section 4.2.2).

The NI may have only grazed the HI feature which is now partially shocked, given that its extreme line-of sight velocity relative to SQ makes it unlikely that it has a very large transverse component. The fact that we detect both SQ and NI emission along the same line of sight at various places along the shock support this interpretation. If the elongated shock arose from a transverse, rather than line-of-sight, component in the NI velocity we might expect to observe an eastward displacement of the SQ emission regions relative to those with NI velocities. Existing data finds them along the same line-of-sight. In any case we can not view the preexisting HI feature as a "wall" but instead as an old tidal feature with well defined extent. Of course we cannot rule out the existence of more extended HI (or X-ray emission) across a much wider part of SQ. In fact the large line of sight velocity difference makes it likely that the bulk of the shocked gas should be along the line of sight if there is any gas to shock in that direction. If present it may have a column density too low for detection (in HI or X-ray). The "missing" X-ray emission (see Section 2.1) may originate in this line of sight component. Evidence for a more diffuse optical emission component comes from Figure 4a where we see very extended and faint emission in addition to that associated with the N-S shock zone. It is reasonable to assume that most of this is probably diffuse [NII] emission.

Emission from the stripped ISM in SQ will involve two components: 1) photoionization recombination emission (e.g. Hα) from denser emission regions associated with star formation and 2) forbidden emission from low density shocked gas (e.g. [NII]λ6583Å). Post-shock emission regions can be distinguished from pre-shock NI emission by the considerable difference in velocity. Shocked gas will brake from near 5600-6000 km/s to 6400-6700 km/s. Optical emission from the shocked gas should follow the radio continuum and X-ray emission and this is confirmed in Figures 2abcd. Our Fabry-Perot measures along the shock are often difficult to interpret. The forbidden [NII] emission is often so broad that it cannot be isolated as a line even with 950 km/s free spectral range. Pre- and post-shock emission regions are both detected in several places along the shock zone where the Fabry Perot measures show two emission line peaks, one at NI (5400-6000 km/s) and the other at SQ (6300-6400 km/s) velocities. We may be detecting recoil in the shock zone because SQ velocities are $\sim$300 km/s lower than unshocked HI N and S of the shock.

Comparison of ISO MIR 11.4 (Figure 8a) and 15μm (Xu et al. 1999 and contours in Figure 8b) with the Hα images shows a weak correlation in the sense that only weak evidence for a MIR ridge or enhancement is seen along the shock zone. This is in marked contrast to the situation for galaxy

pairs where FIR and especially MIR correlate strongly with Hα emission (Xu & Sulentic 1991; Toledo et al. 2001, Domingue 2001). MIR emission is weaker in the shock region than expected, for example from the shock/starburst A ratio for Hα emission. The ratio of continuum subtracted Hα flux (a 100 arcsec^2 region located 40 arcsec south of starburst A for the shock measure) is R$\sim$0.3-0.4$\pm$0.1 while the corresponding 11.4μm ratio is R$\sim$ 0.14$\pm$0.1. Therefore we suggest that MIR emission may be suppressed in the shock region. If this is true then MIR/FIR measures will underestimate the star formation rate in the post shock gas. The weakness of the MIR emission along the shock may be telling us that much of the dust has been diffused and/or destroyed by sputtering in the shock region

One very bright emission region is seen at the immediate edge of the N-S shock. ISOCAM starburst A with V=6670 km/s is a strong source of Hα+[NII], MIR (Xu et al. 1999), HI and CO (Smith & Struck 2001) emission. This is a complex region where both HI and CO spectra show two strong and narrow velocity peaks (6000 and 6700 km/s). Our Fabry-Perot measures indicate that all of the emission regions north of starburst A originate in the NI and account for the 6000 km/s detections. Starburst A is either: a) a condensation of gas at the very edge of the most intense shock region (the SQ ISM at starburst A has been compressed but not shocked) or b) it is an unusually dense region that has cooled out of the shock more quickly than adjacent regions. Local conditions have favored the conversion of much of the gas into molecules M$_{HI}$= 1.5-5.0$\times$10$^9 M_\odot$ and M_{H2}=1$\times$10$^9 M_\odot$)(Smith & Struck 2001). It is difficult to give a reliable estimate for the Hα intensity or equivalent width from our calibrated interference filter images. The relative strengths of starburst A and B (Xu et al. 1999) are more different than the EW values suggest (e.g. the starburst B/A EW ratio=0.74 while the flux ratio= 0.11). The apparent EW similarity arises more because of the relative intensity of the adopted normalizing continuum. Both intensity and EW values also depend upon the correction for [NII] contamination which is maximally uncertain in the SQ shock region. Starburst A appears to be heavily reddened based on Figure 8b where it is the only bright emission region that is distinctly red in color (B-R=1.3 compared to B-R=0.5-0.7 in emission regions just north of it; Mendes d'Oliveira et al. 2001). In fact this appears to be the effect of strong Hα+[NII] emission in the R band because we derive B-V=0.5$\pm$0.05 from the WFPC data. In the absence of high s/n slit spectra, the MIR data (Xu et al. 1999) are a more reliable estimator of the star formation rate in this case (B/A 15μm flux ratio= 0.15 much more similar to the Hα flux ratio). Starburst A at the edge of the shock region is almost 10$\times$ more intense than starburst B at the end of a tidal tail produced $\sim$4$\times$10^8 years ago.

4.2.2. New Intruder ISM and Configuration

The main goal of this section is to discover the properties of the NI. It is difficult to construct a 3D model of the galaxy because there is significant if not complete stellar–ISM decoupling. The stellar disk is traveling through SQ with such a high velocity that it probably remains little disrupted. Identifying the stripped disk of the NI is particularly difficult because: a) it will be

projected on the bright galaxies and tidal debris in SQ and 2) parts of the NI may pass around both sides of the HI clouds in its path and avoid being shocked at all. Our conclusion that the NI ISM is not completely shocked is well supported by the F-P and HI data which resolve considerable confusion about the nature of the nonstellar matter around NGC7318ab. N and SW of NGC7318ab we see chaotic concentrations of emission regions in Hα (Figure 4b) as well as the CFHT B-band image (Figure 9a). They are even more clearly seen on the CFHT B-R image because of their blue color (white in Figure 9b) relative to the much redder underlying stellar light.

The bluest concentration of emission regions (we measure B-V=0.3-0.5 $\pm$0.05 on the WFPC2 images) is seen just north and likely passing in front of starburst A (Figure 10e). The equivalent emission regions to the S and SW of NGC7318ab are fainter (excluding the 4 largest and brightest condensations nearer to the center of the NI) which may indicate that they are on the far side of the NI and more affected by the complex dust lanes and patches that can be seen especially well on the CFHT and WFPC2 images. The optical feature extending northward from NGC7318a toward the blue condensations (variously referred to as a tidal tail or arm) is confirmed as NI material by the detection of a few HII regions (at both ends) with velocities that are internally consistent and that connect smoothly to the northern emission regions. Figure 5b shows the HI clouds with NI velocities: a) 5600-5800 km/s located SSW of the nucleus and b) 5960-6020 km/s located N of the nucleus. Wherever HI clouds overlap (Figure 5b) we find excellent agreement between HI and Fabry-Perot velocities. There is evidence for a residual rotation pattern in the NI emission regions over the range 5400-6000 km/s: from 5400-5700 towards the S and SW, increasing to 5800-6000 km/s towards the W and N. Velocity gradients in the two HI clouds are consistent with this trend. The two distinct Hα+HI concentrations suggest that the ISM of the NI has been split, in the sense that the gas between them has been shocked/displaced but the angular momentum associated with this residual ISM has not been dissipated–further support for the hypothesis that the collision is ongoing. NI emission regions that collide with the SQ ISM at such high velocity will be shocked and ablated. At the same time HI will be rapidly heated in the shock. We therefore conclude that the complex HI+Hα structure W of the shock involves HII regions either not yet shocked or ones that have missed the shock entirely. No emission around NGC7318a (nothing W of the shock–except possibly at the extreme NW edge of SQ) was found to have a velocity within 600 km/s of the nuclear velocity of NGC7318a. The lack of any emission regions attributable to NGC7318a is consistent with its classification as an elliptical galaxy (see also Moles et al. 1998).

The deep CFHT images offer the best chance to make a reasonable estimate of the size and shape of the NI. On the B and R IMAGES we can detect much faint structure that is roughly symmetric about the central bulge of the NI. The NW edge of the disk is particularly well seen with much faint flocculent structure. This structure trails in the same direction as the arm that extends from the edge of NGC7318a towards the HII condensation north of starburst A. The SW extent of the NI is indicated by the HI cloud and Hα concentration (Figure 5b). The distribution of HII regions there is extremely chaotic. Pairs of very bright HII regions on the SW side of the NI flank an apparent break in a ring or spiral arm. Emission regions in the gap between the bright

emission knots are displaced towards the SW by several kpc. All of this region is enveloped by one of the NI HI clouds. Perhaps this region passed directly though NGC7318a. The northernmost emission regions belonging to the NI extend north of starburst A and eastward from the shock near to the north edge of NGC7319. Our B-R image (Figure 9b) may provide the most valuable clue towards unravelling the outermost spiral arms in the NI. It shows a collection of faint blue condensations emerging from the SE side of the central bulge/bar and passing across and south of the brightest HII regions mentioned above. This faint chain of emission regions passes across the N edge of NGC7320. This feature connects with the HII concentration on the SW edge. One region within NGC7320 (region B1 of Arp 1973) and all regions to the SW are confirmed to show NI velocities. We suggest that these emission regions trace the outermost NI spiral structure. In fact this feature connects more smoothly with the east end of the NI bulge/bar structure than does the bright string of emission regions closer to it. The latter appear to be most directly involved with the shock at this time.

The ellipse superimposed on Figure 9b encloses all of the structure that belongs to the NI on the basis of kinematic or morphological continuity. The outermost southern spiral arm seen on the B-R image has a reasonably symmetric counterpart on the opposite side that involves the arm passing behind or in front of NGC7318a and extending north of starburst A. CFHT and HST images suggest that this material is residual spiral structure–filamentary structure involving both bright and dark lanes are clearly visible here. All observations indicate that the NI is/was a large spiral galaxy especially given: a) the amount of atomic and molecular gas that can still be assigned to it and b) given the residual rotation found in the velocity measures (ΔV$\sim$600 km/s). If we assume that the arms trail, the sense of rotation sees the N side nearest and receding. The major axis diameter of the ellipse in Figure 9b is $\approx$2.6 arcmin$\sim$65kpc and the minor axis $\approx$1.6 arcmin$\sim$ 40 kpc which implies an inclination to the line of sight in the range of 30-40°.

The fact that: 1) SQ shows an HI deficit despite the number of well defined HI clouds found there (Figures 5ab; Williams et al. 2001) and 2) that almost 1/3 of our X-ray photons cannot be assigned to a discrete source provide some support for the hypothesis that there may be shocked gas across the broad extent of the NI (our upcoming NEWTON observations will be more sensitive to such emission). The well defined arc that defines the shock at X-ray, radio continuum and optical emission argues that part of the NI, the stripped part, maybe E of the shock. Alternately, if the bulk of its motion is along the line of sight, one can argue that the edge of the NI is brushing past an old tidal HI feature as discussed earlier and suggested by Figure 5a. In this scenario a significant part of the NI may never be shocked. The strongest argument for a significant component of motion towards the NE involves the extensive structural smearing seen in luminous and dust-related absorption features on the N and E side of the NI (Figure 10f). One can see long luminous filaments extending for more than 20-30 kpc in Figure 9a. They extend from near the center of the NI towards the northeast. A prominent dust lane is the southernmost of these features which extends from the NI directly towards the nucleus of NGC7319 (Figure 9a; also visible on the photographs of Arp 1973). This structure does not look like residual spiral arms because it is too

filamentary. The closest analogy one can find involves the spokes of the Cartwheel galaxy (Struck-Marcel & Higdon 1993; Struck et al. 1996). Perhaps the analogy to the Cartwheel is reasonable if the disk of the NI has passed directly through NGC7318a.

We earlier proposed that the intrusion of the NI was not only recent but ongoing. Aside from the timescales cited earlier the bright emission knots south of the NI and NGC7318a may provide the most direct evidence. These features complicate any interpretation of the overall pattern of the NI. They appear anomalously bright and large (the largest show diameters of 400-500pc) compared to other emission regions with NI velocities. One must concede to Arp (1973) that there are HII regions in SQ both larger and more luminous than any in NGC7320 which is almost ten times less distant. The SE string of these emission regions appear to connect to the E end of the bar in the NI. Our CFHT B-R image suggest that instead a fainter arm passes from the bar and defines the south edge of the NI disk. The very bright features may perhaps be part of a disrupted internal ring. Whatever their origin we suggest that they represent NI emission regions in the process of ablation at the shock boundary. At this boundary HII regions will expand in directions perpendicular to the direction of motion assuming a pancake like shape as they become optically thin and dissipate. Little theoretical modeling exists for such a scenario possibly because such a situation is likely to be rare. The more common but equivalent scenario involves emission knots in a hot stellar wind. In either case a large amount of NI kinetic energy will be converted into mechanical energy at the shock front. This energy will heat the SQ ISM as the NI emission regions are ablated giving rise to the observed X-ray and forbidden optical emission. At the same time compression of the ISM and associated magnetic fields will increase the density of nonthermal electrons giving rise to nonthermal radio emission. Some of the elongated emission features in the shock front resemble the expected shape of Rayleigh-Taylor instabilities or "fingers" that are expected in such a medium if the magnetic field lines are more or less perpendicular to the shock front and are compressing the gas against motion along the shock. A candidate instability feature is shown near the top of Figure 10h but many can be seen on archival WFPC2 images.

If our interpretation is correct then we have direct evidence for a shock component along the line of sight because the largest HII regions are west of the shock. If they are ablating then we know that the shock geometry is much more complicated than implied by the N-S "arc". Surprisingly little high s/n spectroscopy exists for emission regions in the NI. Two slit spectra, one published (Gallagher et al. 2001) and one unpublished (J. Gallagher, private communication) exist for the region of the bright knots between the NI and foreground NGC7320. These spectra show typical narrow emission line emitting HII regions with NI velocities. They also show very broad and diffuse emission regions with SQ velocities. Some evidence is also seen for more normal HII regions with SQ velocities. We interpret these as pre-shock, shock and post-shock features. The published 10m HET spectrum (Gallagher et al. 2001) intersects Table 2 emission regions 1, 2 and 3 and then passes just SE of knot 6. The former three regions show somewhat broad emission lines with unambiguously NI velocities. More diffuse gas between knots 3 and 6 shows velocity smeared emission (possibly at V $\sim$6050 km/s intermediate between the NI and SQ) presumably at the shock front. The region

just SE of knot 6 (which has an NI velocity), shows weak somewhat diffuse emission at an SQ velocity. Our IF images (Figures 4ab) show strong SQ and NI emission in this region. This is a part of the shock front where ongoing ablation is occuring. North of this region and inside the emission arc we see possible evidence of HII regions already destroyed in the form of diffuse disk- or ring-like features (see Figure 10h and wider field archival WFPC2 images). The region where the HII region "ghosts" are seen lies directly east from the central regions of the NI where an X-ray, radio and [NII] emission peak is observed. An alternative interpretation might view these features as supernova remnants. The SQ-NI interface appears to be an ideal laboratory for studying the ablation of emission regions in a galaxy ISM.

5. SUMMARY AND IMPLICATIONS

5.1. Galaxy by Galaxy

Proceeding from W to E we summarize our interpretation of the evolutionary history for each galaxy in SQ. While some of these results were reported previously, most or all of our inferences benefit from the first-time unraveling of HI and HII velocities (from the Fabry-Perot and HI measures) throughout SQ.

- **NGC7317** is an elliptical member linked to the rest of the group by diffuse stellar light (Moles et al. 1998). There is no evidence for its involvement in any of the events discussed above.

- **NGC7318a** is an early-type galaxy adjacent to the NI. There is a multi component tidal tail (from N to S: HI–shock zone–HI tail+old optical tail) located E of this galaxy that may point to an earlier metamorphosis from spiral to elliptical morphology. It is interesting that NGC7318a is a stronger source at X-ray and radio continuum wavelengths while NGC7317 and 7318b are not. Published B, V and R magnitudes for these three galaxies (in the case of the NI we are referring to the luminous elliptical-like bulge component) differ by less than 0.5 while they show almost identical colors (Hickson et al. 1989; Schombert et al. 1990; Moles et al. 1998). WFPC2 images shows dust lanes crossing near the nucleus. This galaxy may be a good candidate for infall of tidal debris since the NI disk likely passed through it.

- **NGC7318b**, the NI, is a large gas rich spiral galaxy now entering SQ for the first time with line of sight velocity near 1000 km/s. It is entering the group from behind with a component of motion towards the ENE. Half or more of its ISM is now stripped. The residual ISM is split into two clouds of HI, HII regions and molecular gas with mean velocities near 5700 and 6000 km/s.

- **NGC7320** is a foreground Sd dwarf projected on the southern edge of SQ and directly upon the northern extension of the older tidal tail. HII regions associated with both SQ and the

NI overlap its N end.

- **NGC7319** is an SBb spiral (with Sy2 nucleus) SQ member that has lost most of its ISM. The new tidal tail appears to trace the passage of the OI from NW to SE. In the last intrusion the OI passed just W of the bar in NGC7319 and above (or below) the disk. All detectable HI from NGC7319 is now located in a complex cloud displaced almost one galactic diameter ESE. One or two candidate tidal dwarf galaxies may be forming in this largely quiescent stellar and gaseous debris. Residual Hα and (significant) H_2 gas are found in (or projected on) the NE side of NGC7319 opposite the path of the OI. Some of the gas that was not stripped may have fallen into the nucleus therebye triggering the AGN. It is in transition from spiral to lenticular morphology.

- **NGC7320c**, the OI located one group diameter ENE, shows evidence of a ring and spiral arms, but no trace of HI and weak optical line emission. It is interpreted as the OI because both optical tidal tails curve in its direction. It lost most of its ISM during a passage through SQ and is now bound to the group. It is in transition from spiral to lenticular morphology.

- **SQ** Interactions in SQ are of two kinds: 1) non-impulsive ($\sigma_V \sim 0$, line of sight, for NGC7317, 7318a, 7319 and 7320c) quasi-continuous interactions between bound members and 2) episodic highly impulsive intrusions by neighbors from the associated large scale structure. It may be unusual that two intruders have visited SQ within the last Gyr but the frequency will depend upon the richness of the associated large scale structure and the mass of the attractor. In terms of galaxy surface density, SQ is not unusual (Sulentic 1987). Nonimpulsive interactions will create halos, possibly ignite AGN, and dissipate angular momentum while the more violent collisions can modify member galaxies morphologically (ISM stripping, disk disruption, accelerating the halo building process). Following this definition, both the OI and NI have been involved in interactions of the second kind. Either the OI lost a large amount of kinetic energy in the last visit or the close encounter with NGC7319 was slow and remarkably efficient. The young tail and associated HI cloud supports the latter hypothesis. If the ISM of galaxies in SQ was largely lost to impulsive encounters then it will be dangerous to extrapolate the SQ experience to other groups, unless the DM haloes foster rapid and efficient dissipation of intruder kinetic energy.

  SQ has survived significantly more than 1 Gyr without any evidence for onset of merging. As far as it goes this suggests that mergers may be very rare among compact groups. They must occur before the disruption/stripping process is too advanced or they will be unable to achieve extreme or even unusual IR luminosities (Borne et al. 2000). SQ suggests that the proximity and strong interaction of 4-5 galaxies does not always lead to rapid coallescence although it does lead to efficient stripping of component ISMs. The latter results in depressed rather than enhanced star formation activity. It is unclear what role the episodic intrusions play in retarding the coallescence or whether the fate of the group is determined mostly by the properties of the dark matter halo thought to surround such groups. The observations

suggest that it accounts for ∼90% of the mass (to accelerate high velocity intruders) and that it is distributed very smoothly resulting in a very diffuse, rather than cuspy, potential.

5.2. Implications for High Redshift Phenomena

Compact groups manifest the galaxy formation and evolution processes that are invoked to describe and explain what we see at high redshift. Interactions and the effects of interactions are believed to be more frequent in the past (e.g. Wu & Keel 1998). Compact groups as the site of extreme interactions at low redshift may therefore be useful local analogs that can be studied in greater detail. We consider the implications of SQ to various topics often discussion in a high redshift context.

- **1) Infall processes and structure formation in the Universe:** SQ suggests that compact groups form by the sequential acquisition of, sometimes high velocity, intruders from the associated large scale structure. Other Hickson groups also show internal high velocity (likely) intruders and potential intruders just outside the isolation boundary (Sulentic 1987). We can identify with some confidence the two most recent (within the past 1Gyr) arrivals in SQ. While not cataloged as a member of SQ the OI is now likely bound to the system. The NI is likely a giant field spiral that we find in mid passage. The NI shows a cluster like velocity relative to SQ. If SQ is responsible for this high infall velocity then a significant nonbaryonic mass component is required because the baryonic mass fraction in SQ is an order of magnitude too low to serve as an efficient attractor (Moles et al. 1997). Limits on the rapidity of formation and frequency of occurence of this process will be set by the number of observed groups and the density of galaxies in their local environment.

- **2) Dynamical evolution:** SQ shows classic signs of repeated interactions such as tidal tails and diffuse light. SQ suggests that interaction with existing and incoming members leads to the gradual stripping of both gas and stars from group members. Two recognizeable spirals in SQ are almost totally stripped: NGC7319 and the OI are almost certainly evolving into E/S0 systems. SQ suggests that compact groups evolve from predominantly spiral to early-type systems. Early-type rich compact groups are found locally but their numbers, as evidenced by the Shakhbazian groups (e.g. del Olmo et al. 1995), appear to have been larger at higher redshift. The early-type rich compact groups would be the highly evolved analogs of SQ that are most resistent to merging. HCG79 (Seyfert's Sextet) may be the best low redshift example. If such groups indeed originated from gas rich spirals then the most intriguing question is "where did the gas go?".

- **3) Star Formation and ULIRGS:** Compact groups do not show high average levels of star formation as inferred from their MIR/FIR emission (Sulentic & deMello Rabaca 1993; Verdes-Montenegro et al. 1998). This is in contrast to what is seen in pair samples found

in similar environments (e.g. Xu & Sulentic 1991). Dynamical evolution in SQ-like groups will leave most gas either too hot or too cold to support much star formation. In SQ the strongest residual starburst activity is of an unusual kind –modest starbursts in tidal debris. No Hickson group shows extreme IR properties (LIRG or ULIRG). Reasonably strong IR emitting groups are often dominated by an AGN. In the case of SQ there is no evidence that even that IR emission is driven by star formation. The rare examples of high redshift ULIRG compact groups (Borne et al. 1999) are likely different from the average Hickson (i.e. nearby) group. They are interpreted as multiple mergers *in flagrante delicto* while SQ shows no evidence for merger activity and much evidence for systematic metamorphosis from a spiral to an early-type rich system. Unless an ULIRG can form from a group that is largely stripped, they must be the most "unlucky" compact groups where component galaxies arrive at about the same time (avoiding systematic disruption of the individual DM haloes) and quickly evolve to coallescence. Such groups are rare.

- **3) Feedback and the formation of AGN:** SQ contains a stripped spiral with Seyfert 2 nucleus that may have arisen because of the violent dynamical processes occuring there. The quasi-continuous nature of the tidal torques in compact groups may more efficiently (than in pairs) channel gas into the nuclear regions of group members. This process, or feedback of stripped gas, could give rise to the excess of nucler radio sources (Menon 1995) and type 2 AGN (Coziol et al. 2000). It is perhaps too soon to expect more systematic feedback of stripped gas into the component galaxies of SQ. NGC7318a may be the best candidate for tidal feedback since it is in the path of the NI disk. The general HI deficit found for the groups (e.g. Verdes-Montrenegro et al. 2001) may be evidence that such feedback is very slow and inefficient.

- **4) Merger phenomena:** A conservative age between 1-2Gyr can be assigned to the identifiable episodes of intruder activity in SQ. SQ is dynamically evolved and all members except the ongoing intruder have lost their ISM. Unless significant gas feedback occurs it is therefore difficult to envision a fate for SQ as an infrared bright (ULIRG) merger (Borne et al 1999). If one wants to make an ULIRG then one must do it quickly before massive stripping occurs but after the dark matter halo is disrupted. If SQ is typical of compact groups then this requirement is rarely fulfilled. Yet the velocity dispersion in SQ $\sigma_V \sim 0$ (excluding the unbound NI) is fairly common in local groups. Evolving ideas about massive and diffuse DM halos around the groups may also be converging with observations that suggest that even low velocity dispersion groups can resist merging indefinitely (Athanassoula et al. 1997).

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Fig. 1.— The six panels provide finding charts for each galaxy in SQ where the recession velocities and aliases are also noted. Other important features discussed in the text are identified. New and old tail in the lower right panel are, respectively, synonymous with younger and older tail in the text.

Fig. 2.— Comparison of the X-ray maps from the new HRI observation of Stephan's Quintet with radio continuum and [NII] line + red continuum emission: UPPER LEFT (a): an adaptively smoothed HRI image with superposed contours. UPPER RIGHT (b): the adaptively smoothed HRI contours superposed on a 21cm radio continuum image (18 arcsec synthesized beam) with comparable effective resolution. LOWER LEFT (c): a Gaussian smoothed ($\sigma = 4''$) HRI image. LOWER RIGHT (d): an interference filter image centered at λ 6731Å (FWHM=10Å) sensitive to [NII]λ6583Å (+ continuum) emission in the SQ velocity range 6460-7000 km/s.

Fig. 3.— LEFT: Plot of the regions used in Table 1 to derive fluxes of the different components and of the residual emission. RIGHT: Radial distribution of the total emission from SQ, azimuthally averaged in two arcs oriented NS and EW, in concentric annuli about the X-ray peak roughly in the middle of the elongated N-S extended source. The adopted background level is also shown. The excess at r$\sim 1'$ is due to the Seyfert nucleus. Data are from the new observation only.

Fig. 4.— UPPER: Interference filter images. LEFT (a): Continuum-subtracted line image centered at 6738Å which includes Hα and [NII] emission from SQ. There is contamination from [NII] in the new intruder. RIGHT (b): Equivalent image centered at 6668Å and imaging Hα emission in the new intruder. Contour maps for a) and b) with appropriate flux levels can be found in Xu et al. (1999). The nuclei of NGC7317 as well as NGC7318a and b are marked with an "X". Scale can be obtained from the 21 arcsec separation of the X's for NGC7318a and b.

Fig. 5.— LOWER: HI 21cm radio contours superposed on above images. LEFT (c): HI contours for velocities in the SQ range 6475-6755 km/s. RIGHT (d): HI contours for velocities in the new intruder range (5597-6068 km/s). HI contours levels correspond to 5.26e19, 1.58, 2.63, 5.26, 7.89×10^{20} cm^{-2} with last contour shown only in Figure 4c.

Fig. 6.— The lower part of the schematic shows the wavelength ranges for Hα and [NII]λ6583 emission in SQ and the new intruder as well as [SII]$\lambda\lambda$6717,31 emission in foreground NGC7320. The upper part shows the wavelength ranges sampled by various filters and Fabry-Perot observations reported here and elsewhere. In the top panel "Plana et al." refer to published CFHT and Russian 6m F-P observations of Plana et al. (1999). SPM IF and CA IF refer to interference filter images obtained at San Pedro Martir and Calar Alto respectively while SPM F-P refers to Fabry-Perot observations taken with PUMA at San Pedro Martir.

Fig. 7.— Identification charts (Hα contours) for all emission regions with measured velocities from our Fabry-Perot observations for (a) SQ ([NII]λ6583) and (b) the NI (Hα). Velocities for the identified features are found in Table 2.

Fig. 8.— ISO images of SQ: a) 11.4μm MIR ISOCAM and b) 60μm FIR ISOPHT. Images are in log scale. The display range for the 11.4μm image is [0.01, 10] mJy/pix (6 arcsec square pixels). The 15 micron contours are 0.1, 0.2, 0.3, 0.4, 0.8, 1.1, 1.4 and 1.7 mJy on a 60μm image with a display range [0.1, 10] mJy/pix. The bulk of the emission originates from the Seyfert 2 nucleus of NGC7319 and the late-type foreground spiral NGC320.

Fig. 9.— a) CFHT-B and b) B-R images of SQ. The inferred size of the new intruder is indicated by an ellipse in b) which is windowed to emphasize the bluest features (white). Using the same data Mendes de Oliveira et al. 2001 measure B-R=1.32 for SQ starburst A and B-R=0.4-0.7 for the blue intruder emission regions north of it.

Fig. 10.— Vignettes of eight sources or regions in SQ taken from the average B-band WfPC2 image obtained with Hubble Space Telescope. The finding chart is an R-band image obtained with the CA 1.5m telescope (see Moles et al. 1998). Vignettes show: A) the region of ISO starburst B in the younger tidal tail with associated dust lane; B) Very blue stellar concentration at the tip of the younger tidal tail. C) Emission region near the north edge of the stripped HI cloud; D) NE corner of NGC7319 showing a concentration of blue stars on the end of the ring as well as a large (possibly superposed) dust patch; E) region of starburst A (lower left) and superposed intruder emission regions and dust lanes; F) region of the new intruder and the shock front between starburst A and new intruder central bulge showing radial features (structural smearing or spokes as in the Cartwheel); G) portion of the disrupted arm or ring of new intruder with ablating HII regions; H) The center of the shock with debris of ablated HII regions and an emission ring (S edge).

Table 1: Net counts, fluxes and luminosities for the different HRI components in Stephan's Quintet. Fluxes and luminosities in the 0.1-2.0 keV range are derived from the total count rates with a conversion factor of 3.9×10^{-11} ergs cm^{-2} s^{-1} and are corrected for the line-of-sight absorption. The useable integration time is t= 77.5 ks.

Comp.	Net counts			Intrinsic X-ray Flux	X-ray Luminosity
	old	new	total	(erg cm^{-2} s^{-1})	(erg s^{-1})
total r< 3′	370±48	833±78	1203±92	6.1×10^{-13}	5.3×10^{41}
total r< 1.5′	305±28	703±45	1008±53	5.1×10^{-13}	4.5×10^{41}
Sey	45±8	117±13	162 ± 15	8.2×10^{-13}	7.2×10^{40}
shock (int)	66±9	164±15	230 ± 18	1.2×10^{-13}	1.0×10^{41}
shock (ext)	121±15	338±25	459 ± 29	2.3×10^{-13}	2.0×10^{41}
N7318a	24±6	37±8	61 ± 10	3.1×10^{-14}	3.7×10^{40}
NW ext.	11±5	28±8	39 ± 9	2.0×10^{-14}	2.4×10^{40}
residual r< 1.5′	105±22	183±34	288±41	1.4×10^{-13}	1.3×10^{41}

Table 2: ISO MIR and FIR FLUXES

SOURCE	$S_{11.4\mu m}$	$S_{60\mu m}$	log $L_{60\mu m}$
ID	mJy	mJy	$L_\odot$
NGC7319	47.5	529	9.83
NGC7320	59.8	487	7.92
NGC7318ab	34.5	>24	>8.34
Starburst A	14.1	79.5	8.98
Starburst B	0.3		

Table 3: FABRY-PEROT (and other) VELOCITIES

Intruder				Stephan's Quintet		
Region #	F-P	Plana vel.	Lit. (km s^{-1})	Region #	F-P vel. (km s^{-1})	Identif./Notes
1	5636*	–	5550h	38	7078+	
2	5635*	5580	5400h/5594f	39	6800*	
3	5680*	5640	5700h/5623f	40	6627+	
4	5640+	–		41	6617*	starburst B
5	5708*	5715	5860e	42	6690*	starburst A
6	5727*	5715	5717o/5540/6500h	43	6725*	NGC7319 Seyfert nucleus
7	5766+	5740	6460	44	6422+	
8	5775*	5750	6460	45	6350/5987+	
9	5750*	–		46	6370-	
10	5737*	–		47	6370-	
11	5795*	5765		48	5990+	
12	5731*	–		49	6000+	
13	5699*	–		50	6350/6056+	
14	5766*	–		51	800+	NGC7320 [SII]
15	5770*	5730				
16	5780*	5755				
17	5660*	–				
18	5810+	5815				
19	5830*	–				
20	5890*	5855				
21	5715+	–				
22	5860-	–				
23	5959*	–				
24	5921+	5935				
25	5940-	–				
26	5979*	5950	6020			
27	5990*	5960	6020			
28	5990*	–				
29	5988+	5960				
30	6017*	–				
31	6010*	5985				
32	6000-	–				
33	6017-	6005				
34	5987-	6000				
35	5997-	–				
36	6036-	–				
37	5959+	–				

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